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Linear Regression		
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STATISTICAL ANALYSIS OF WEEKLY AVERAGED RADON LEVELS IN THREE RESIDENCES OVER A COMPLETE YEAR

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ABSTRACT

This paper presents results of a statistical analysis of weekly averaged indoor radon levels in three residences in the Princeton, New Jersey, area for which year-long continuous measurements of radon and other climatic and house parameters were available. It presents and discusses linear regression models of indoor radon identified based on physical considerations rather than on those that yield the highest goodness-of-fit to actual data. Finally, certain aspects related to the experimental design of the instrumentation protocol are also addressed.

INTRODUCTION

The Center for Energy and Environmental Studies of Princeton University has, over the last 3 years (1), compiled a large data base of half-hourly radon levels and other related parameters over several months for over a dozen occupied residences in New Jersey. The present statistical investigation will limit itself to three residences for which the data span almost an entire year. Since the database is continuous, and physically one does expect persistence effects over consecutive time intervals, the proper way to analyze the data is in a time series framework.

The first objective would then be to try to capture the long term or secular trends. Physically this would entail looking at how radon levels in or around a specific house change from year to year as a result of changes in source strength, geophysical characteristics, and occupant activities. This aspect is beyond our present scope primarily because of the lack of adequate data over many years. The second step would be to look at variations during a given year. The third step would be to look at how radon varies during particular periods of the year, while the final step would be to attempt to model diurnal variation.

This paper limits itself to reporting the results of our analysis involving weekly averaged yearly time scales, while those involving other time scales are addressed in Refs. (2, 3). Since the data are limited to a relatively small number of houses in only one climate, that of central New Jersey, the statistical results obtained will probably not be generalizable. However, they may yield some insight into indoor radon's relationship to climatic and house parameters.

DESCRIPTION OF HOUSES AND DATA BASE

This study covers three residences, referred to as PU-2, PU-21, and PU-22, that show distinct and characteristic differences not only in their layout, construction, and subslab conditions, but also in the equipment used for heating and air-conditioning (HAC) the house (see Table 1). These houses were occupied and, except for short periods of time during which we performed intrusive experiments, the various houses and equipment therein were operated naturally by the occupants themselves.

The parameters measured continuously on a half-hourly time scale for all three houses are listed in Table 2. This table also defines the symbols used in this paper. Temperature or pressure difference variables have also been used in this study. For example, DTBA would imply difference between TB and TA variables. The selection of these parameters and the location of the sensors were arbitrary to some extent. They were dictated by a concern to include all the important parameters which influence the house, and thereby the radon dynamics, while avoiding excessive measurements. Consequently, only single point measurements have been made of the various parameters anticipated as influencing radon entry and indoor radon variation. We can conceptually divide these into three groups of increasing hierarchy in terms of ease in measurement and of causality. Specifically, the temperatures, wind, and air-handler on-time can be considered to form a set of basic parameters since in a physical sense they are the cause for variation in the other parameters, namely pressure differences and subsequently indoor radon levels. The effect of resident behavior (such as opening windows) on, say, radon levels cannot be explicitly studied but is assumed to be implicitly present in the data set.

LINEAR REGRESSION MODELS

A previous study (4) has taken a comprehensive look at a large number of the various plausible combinations of linear regression models. We shall present only those which are simple and physically appropriate while yielding satisfactory goodness-of-fit. The goodness-of-fit of the various models is evaluated based on the adjusted coefficient of determination ($\bar{R}^2$) which is superior to the simple coefficient of determination since the number of degrees of freedom is also taken into account.

The radon regression models are summarized in Table 3. The model structure is of three different types: those involving DT and AH, those involving DP, and those involving DP and other radon levels. Looking over the table we note wide variations in $\bar{R}^2$ values for different houses, while the $\bar{R}^2$ values of various models for each house are not very different. The variations in both RNB and RNL are very well explained for PU-21 ($\bar{R}^2 > 0.8$), satisfactory for PU-22 ($\bar{R}^2$ = 0.5 to 0.6), and poor for PU-2 ($\bar{R}^2$ = 0.28-0.34).

Model 1a seems satisfactory for RNB for PU-2 and PU-21 while Model 1b is markedly superior for PU-22. For RNL, Models 1a and 1b are equally good and consequently Model 1a is preferred for the sake of parsimony. It is indeed surprising that this model structure is as good as one involving DP and radon (Model 3), since physically one would not have expected this. As for the regression coefficients of Model 1a, those for PU-2 and PU-22 are fairly consistent, while those of PU-21 are different, probably as a result of the basement window being open during part of the year.

Figure 1 depicts time plots of the observed and predicted radon levels in all three houses. The models are indeed satisfactory for PU-21. As for PU-22, the model for RNB is satisfactory only during summer when the air handler is on. During the remainder of the time periods when AH is small or zero, the model is unsatisfactory, indicating that physical parameters other than DTBA influence RNB. For PU-2, the models seem to have captured the year-long trend, though the week to week variations are not well predicted.

The $\bar{R}^2$ for the models of RNL are higher than those for RNB. This is to some extent surprising since radon generally enters the house via the basement and is then entrained upwards to the living area. The forcing

functions being the same for RNB and RNL, one would have expected models for RNB to have better predictive power. That the $\bar{R}^2$ are widely different, from house to house while those for both RNL and RNB of a given house are not very different, irrespective of the model structure used, is also noteworthy.

Another surprising fact is that the simple models involving only DTBA or DTLA (representative of the stack effect) seem to predict weekly radon variation as well as those models involving DP and other radon values. The result may be due to the fact that our present experimental design involves only single point measurements of a particular parameter in each zone. It may not only be more difficult to select spots at which to place pressure senors capable of yielding zone-averaged representative values, but also the metrologies associated with such DP measurements are generally more complex than DT measurements. This aspect of experimental design needs to be investigated further in the framework of future studies.

A noteworthy feature, regarding the regression coefficients of Table 3, is that they vary among houses. (For the sake of brevity, we have not included the standard errors of these coefficients.) Generally, model coefficients for PU-2 and PU-22 are consistent and fairly close, while those of PU-21 are drastically different, probably because of opening the basement window. This variation not only is a reflection of the house specific nature of these driving variables but also may be due to the inadequacy of a single-point measurement protocol.

SUMMARY AND CONCLUDING REMARKS

The validity of this study rests on the fact that weekly averaged quantities are inherently more stable (i.e., less prone to be affected by a few outlier short-term measurement points) than data over shorter periods of time: therefore, the results of the statistical analysis are likely to be robust and less prone to be misleading. On the other hand, during different seasons of the year, different driving forces could dominate or the same forces could have varying degrees of importance. This aspect has been investigated in another study (2).

This study is perhaps the first of its kind where data for a complete year have been obtained in occupied houses, and where the objective was also to look at how differences among houses would affect these parameters. Though the macroscopic phenomena affecting radon are generally well understood, we have undertaken to model the variations quantitatively, and do so in occupied houses which inherently have higher noise levels due to occupant vagaries. We have also looked at how well a physically relevant model structure explains the observed variation in the response variable and to what extent the coefficients of the model parameters are consistent among houses over an entire year.

The most important conclusion, regarding linear regression models for radon in the three houses studied, is that the single most dominating parameter for explaining radon variations over the entire year is the stack effect (i.e., temperature differences DTBA or DTLA which are strongly covariant). This study also highlights the fact that this natural driving force has varying degrees of influence on indoor radon levels depending on the characteristics of the house. (The HAC effect is secondary but non-negligible, though because of multicollinearity between the DT and AH, the isolated effect of HAC is difficult to evaluate (2)). The reason for the large variation in model $\bar{R}^2$ among houses seems related to the size of the house, to subsoil characteristics, to relative HAC size (i.e.,

dominance of HAC on building shell), and to occupant behavior such as opening or closing of windows.

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REFERENCES

1. Dudney, C.S., Hubbard, L.H., Matthews, T.G., Socolow, R.H., Hawthorne, A.R., Gadsby, K.J., Bohac, D.L., and Wilson, D.L., (1988) Investigation of Radon Entry and Effectiveness of Mitigation Measures in Seven Houses in New Jersey, ORNL-6487, September 1988.

2. Reddy, T.A., Molineaux, F.B., Gadsby, K.J., and Socolow, R.H., (1990) Statistical Analyses of Radon Levels in Residences using Weekly and Daily Averaged Data, PU/CEES Report No. 249, Princeton University, April.

3. Hull, D.A., (1990) Time series linear regression of half-hourly radon levels in a residence, paper presented at the 1990 International Symposium on Radon and Radon Reduction Technology, Feb.19-23. Atlanta, GA. (AEERL-P-610)

4. Molineaux, F.B. (1989) Statistical Analysis of Weekly Radon Levels in Residential Houses, PU/CEES Working Paper No. 103, Princeton University, April.

Table 1 Principal physical characteristics of the three houses selected for this study

PU-2
- Completely exposed to surroundings.
- Two stories with full basement (all sides communicate with ambient).
- Basement has windows which are nailed closed.
- HAC used for both heating and cooling.
- Leaky return ducts in basement.
- Gravel bed under slab.

PU-21
- Fully surrounded by landscaping.
- Medium sized house: single-story with partial basement (only 2 sides communicate with ambient).
- Basement has windows, one of which is opened in summer.
- HAC used for both heating and cooling.
- Leaky return ducts in basement.
- Gravel bed under slab.

PU-22
- Partially exposed to surroundings.
- Large house: three stories with partial basement (only 2 sides communicate with ambient).
- Basement without windows.
- Air handler used only for cooling. Steam heating.
- Second and third floors cooled zonally. First floor not cooled.
- Soil under slab.

Table 2 Description of parameters measured continuously

1.	TB	Temperature of air in the basement, ^{o}C
2.	TL	Temperature of air in the living room, ^{o}C
3.	TA	Ambient temperature of air, ^{o}C
4.	W*	Wind speed measured at the weather station, m/s
5.	TS**	Temperature of soil below the slab of the house, ^{o}C
6.	AH	Air handler (fraction on-time)
7.	DPAB	Pressure difference between ambient and basement, Pa
8.	DPSB	Pressure difference between subslab and basement, Pa
9.	DPLB	Pressure difference between living room and basement, Pa
10.	RNB	Radon level in the basement, pCi/L
11.	RNL	Radon level in the living room, pCi/L
12.	RNS	Radon level under the slab of the basement, pCi/L

* Used in PU-2 only
** Not available for PU-2

(Temperature differences have also been used in the study.
DTBA - temperature difference between TB and TA parameter
DTLA - temperature difference between TL and TA parameter).

Table 3. Regression models for weekly averaged indoor radon in picocuries per liter. Temperatures are in degrees Celsius while pressures are in Pascals.

Model	House	Model	$\bar{R}^2$	No. of Data Points
1a	PU-2	RNB = 14.61 + 0.602 x DTBA	0.36	29
	PU-21	RNB = 16.35 + 10.13 x DTBA	0.75	40
	PU-22	RNB = 36.05 + 0.554 x DTBA	0.06	42
1b	PU-2	RNB = 14.46 + 0.632 x DTBA + 0.980* x AH	0.34	29
	PU-21	RNB =-16.97* + 14.29 x DTBA + 142.0 x AH	0.79	40
	PU-22	RNB = 48.27 - 0.316* x DTBA - 32.39* x AH	0.51	42
2	PU-2	RNB = 16.12 + 1.67 x DPAB	0.24	29
	PU-21	RNB =-21.03 + 90.56 x DPAB	0.83	40
	PU-22	RNB = 31.95 + 5.113 x DPAB	0.12	42
3	PU-2	RNB = 9.17 + 1.107 x DPAB + 0.605 x RNL	0.35	29
	PU-21	RNB = -33.5 + 138.0 x DPAB - 1.113 x RNL	0.87	40
	PU-22	RNB = 28.66 + 2.927* x DPAB + 0.412* x RNL	0.15	26
1a	PU-2	RNL = 9.862 + 0.292 x DTLA	0.30	32
	PU-21	RNL = -11.79 + 6.031 x DTLA	0.84	40
	PU-22	RNL = 4.690 + 0.927 x DTLA	0.56	26
1b	PU-2	RNL = 9.328 + 0.361 x DTLA + 2.518* x AH	0.28	32
	PU-21	RNL = -30.62 + 8.03 x DTLA + 57.49 x AH	0.88	40
	PU-22	RNL = 4.75* + 0.914 x DTLA - 0.788* x AH	0.56	27
2	PU-2	RNL = 10.02 + 1.257 x DPAB	0.30	17
	PU-21	RNL =-11.20 + 42.58 x DPAB	0.84	40
	PU-22	RNL = 1.905* + 5.26* x DPAB	0.59	26
3	PU-2	RNL = 6.790 + 0.443* x DPAB + 0.291* x RNB	0.29	29
	PU-21	RNL =-15.86 + 62.64 x DPAB - 0.221 x RNB	0.88	40
	PU-22	RNL =-0.114* + 4.907 x DPAB + 0.069* x RNB	0.59	26

*Probability /T/ greater than 0.1, where T is the Student t-Statistic.

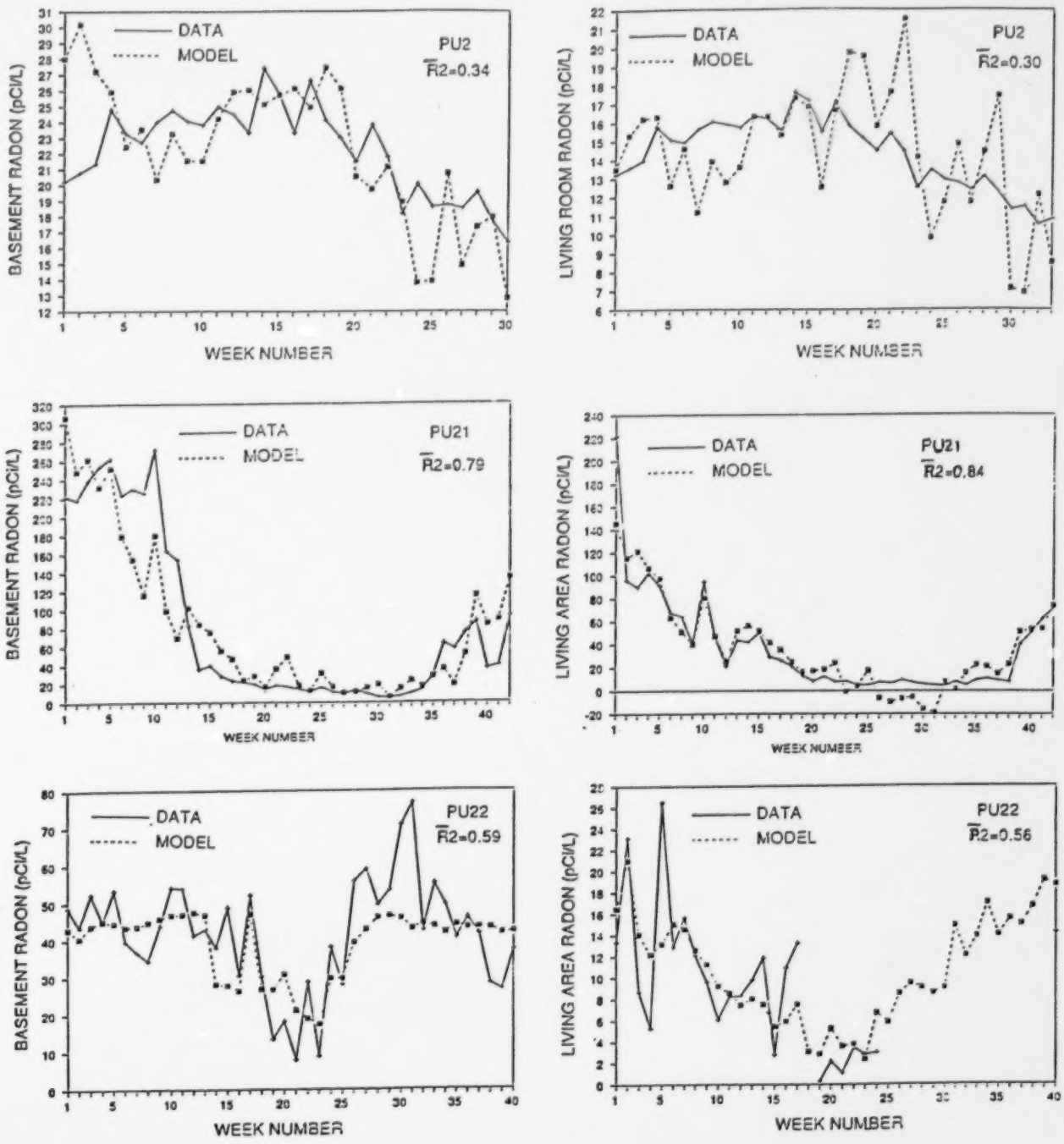

Figure 1. Observed and model predicted time plots of indoor radon levels. Model 1a has been used throughout, except for RNB of PU-22 where model 1b was used.